Mini review

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Sulfate-reducing bacteria-assisted cracking

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Abstract: Field and laboratory studies have verified that sulfate-reducing bacteria (SRB) can assist in cracking, but there is no comprehensive review in literature related to this research. In this paper, a mini-review was done giving the available information on SRB-assisted cracking, including actual cases, laboratory investigations, thermodynamic interpretation, cracking mechanisms, and affecting factors. Furthermore, the existing problems were regularly extracted, and the possible development tendency prospected.

Keywords: corrosion fatigue; microbiological corrosion; stress corrosion cracking; sulfate-reducing bacteria.

1 Introduction

The metal structures serving in the natural environment, such as pipe steels in soils, bridges over rivers, and offshore infrastructures in marine environments, are subjected to corrosion failure and loss of mechanical properties (Wu et al., 2015b). It is generally believed that the failure and loss of metal are related to materials, the environmental conditions, and the stresses under the metals. As for the environmental conditions in the natural environment, the microorganism incubating on the metal surface is one of the most damaging factors for buried pipe

steel in soils (Maruthamuthu et al., 2011; Wu et al., 2015c; Li et al., 2018) and offshore platform in marine environments (Duan et al., 2008; Qian et al., 2017; Xu et al., 2017). The microorganisms' influences on the kinetics for metal corrosion processes and their adhesion to the solution/metal interfaces were defined as microbiologically influenced corrosion (MIC) (Javaherdashti, 2008; Zhou et al., 2018). Sulfate-reducing bacteria (SRB) (Liu et al., 2018a,b), nitrate-reducing bacteria (NRB) (Li et al., 2017; Huang et al., 2018), iron-oxidizing bacteria (Liu et al., 2017), acid-producing bacteria (APB), and fungi (Beech and Gaylarde, 1999; Little et al., 2001) are the typical microorganisms associated with metal corrosion. MIC is thought to account for 20% of the corrosion failure of metal (Little et al., 2006) in different conditions, and much attention was paid to the roles of microorganisms in metal corrosion (Jia et al., 2017; Zhao et al., 2017). Recently, Li et al. discussed the MIC mechanisms using bioenergetics, microbial respiration types, and biofilm extracellular electron transfer (EET) (Li et al., 2018).

In addition, the stress state of metals is another important factor accelerating the corrosion failure of metal infrastructures in the natural environment. Stress corrosion cracking (SCC) (Fang et al., 2006) and corrosion fatigue (CF) (Puiggali et al., 2002) are the typical damaging failure modes induced/accelerated by stresses. They are associated with the static/low-frequency stresses and dynamic stresses (Fang et al., 2005), respectively. In the recent decades, the individual and simultaneous effects of chemical or electrochemical and mechanical factors, such as hydrogen (Lu et al., 2009), dissolved oxygen (Mehta and Gosselin, 1998), dissolved carbon dioxide (Egbewande et al., 2014), pH (Osuke et al., 2012), corrosive ions (Vosikovskiy and Rivard, 1982), load magnitude (Chen et al., 2007), load waveform (Lu et al., 2009), and frequency (Takahashi et al., 2010), on SCC or CF were widely studied in the literature, and many failure mechanisms were proposed in various conditions.

Furthermore, some field investigations (Rao and Nair, 1998; Kholodenko et al., 2000; Abedi et al., 2007; Al-Nabulsi et al., 2015) also verified that microorganisms can enhance the steel cracking under the assistance of the stresses. In April 2004, an API5LX52 pipeline cracked in the northern part of Iran, which led to leakage of amounts

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of oil (Abedi et al., 2007). The subsequent investigation demonstrated (Abedi et al., 2007) that the main cause of the pipeline cracking was SCC induced by carbonate-bicarbonate, but SRB also participated in the process, and then SRB intensified the pipeline pitting corrosion and crack initiation. Russia scholars found that the SCC length of pipe steels in the field was mostly related to counts of SRB and NRB, and the SCC depth was correlated with the number of APB and saprophytes in certain types of soil (Kholodenko et al., 2000). Wilmott et al. proposed a non-classic type of SCC, in which the crack lengths are directly related to the numbers of SRB and APB (Wilmott et al., 1996). APB and NRB were identified as the main cause of 90% of the wall thinning in the heat-affected zone of the girth weld, and the subsequent rupture of the carbon steel (Rizk et al., 2017). The above field investigations demonstrated the simultaneous effects of SRB and stresses. Therefore, it is important to review the available information for a better understanding of this problem.

In this paper, the cracking induced/accelerated by SRB is defined as SRB-assisted cracking (Wu et al., 2018b). The number limited but invaluable reports in the field on SRB assisted cracking were collected in the paper, and SRB-assisted SCC/CF of steels were reviewed. Furthermore, the thermodynamic interpretation and possible mechanisms were summarized in detail. Finally, factors affecting SRB-assisted cracking are also discussed in this paper.

2 SRB-assisted cracking in simulated investigations

2.1 SRB-assisted SCC

Many laboratory studies documented the SRB-assisted SCC for different steels in different environments (Robinson and Kilgallon, 1994; Vaidya et al., 1997; Raman et al., 2005; Javaherdashti et al., 2006, 2012; Domzalicki et al., 2007; Javaherdashti, 2011; Stipaničev et al., 2014; Wu et al., 2014b). When the carbon steel was subjected to the slow strain rate testing (SSRT) in sodium chloride solution, specimens in SRB-inoculated condition showed a considerable loss of ductility, compared to those in sterile condition (Javaherdashti et al., 2006). Fracture morphology of the specimens in sterile condition suggested the feature of only ductile mode (dimples), whereas these in SRB-inoculated condition exhibited the features of both transgranular cracking and ductile dimples (Raman et al., 2005). These showed the higher SCC susceptibility of the

carbon steel in SRB-inoculated condition. Domzalicki et al. documented that the presence of SRB produced an additional plasticity loss of the low-alloy ferrite-pearlite and sorbate steels in synthetic seawater and that their plasticity loss became especially pronounced at cathodic potentials (Domzalicki et al., 2007). Recently, Wu et al. tested the SCC susceptibility of an X80 pipeline steel in a near-neutral pH soil solution and found that SRB individually increased the SCC susceptibility of the steel, whereas the increase depended on the prolongation of pre-incubation time (Wu et al., 2015b). It was also reported that the applied potentials and the presence of SRB worked together in promoting the SCC susceptibility of the steel, but the combination effects became limited with the decrease in the cathodic potentials (Wu et al., 2015b). Wang et al. also found the positive role of SRB in enhancing the SCC process in an acid solution (Wang et al., 2017a). Furthermore, it was reported that SRB could decrease the threshold stress-intensity-factor (K_{th}) for SCC of the 500 and 690 alloy steels in the marine environment (Robinson and Kilgallon, 1994).

The above studies demonstrated that the physiological activity of SRB resulted in the ductility loss of steels, increased their SCC susceptibility, decreased their SCC K_{th} , and induced the transformation from ductile mode to brittle failure.

2.2 SRB-assisted CF

SRB-assisted CF was also investigated in the simulated laboratory environments in the literature (Thomas et al., 1987; Huang, 2004; Sowards et al., 2014). It was shown that CF can be enhanced by marine fouling on an offshore structure (Thomas et al., 1987). The biologically produced H_2S not only increased the crack propagation rate but also reduced the threshold stress intensity factor amplitude (ΔK_{th}), showing that the biologically produced H_2S overcame the crack tip blunting effect. However, at the levels of ≈ 200 ppm and above, biologically produced H_2S was a less potent fracture agent in seawater than non-biologically produced H_2S (Thomas et al., 1987). The low-cycle life of the 10KhSND steel was reported to be related to the intensity of the development of *Bacterium* and *Pseudomonas* (Tsokur and Kobzaruk, 1984). Sowards et al. evaluated the effects of SRB and APB on the fatigue-crack propagation of ASTM A36, API 5L X52, and X70 steels (Sowards et al., 2014). The fatigue testing showed that SRB and APB markedly increased the fatigue crack propagation rates of these steels (Sowards et al., 2014). In diluted Postgate medium C solution, SRB were reported to greatly enhance

CF crack propagation rates and reduce CF crack initiation life of the HY130 steel under cathodic polarization (Gangloff and Kelly, 1994). As a result of the presence of SRB, the fatigue mode was changed into intergranular cracking from transgranular under the cathodic protection (CP) at the constant ΔK (Gangloff and Kelly, 1994). Furthermore, SRB-assisted CF was also recorded in sea-mud for marine steel by Huang (2004).

The above examples manifested that SRB reduced crack initiation life and ΔK , enhanced crack propagation rate, and changed the CF mode and that biologically produced H_2S played important roles in these processes. For safety, the deeper investigations on SRB-assisted cracking are required for more steels in a wider range of environments.

3 Mechanisms of SRB-assisted cracking

It must be confessed here that the mechanisms stated in the paper are only the possible explanations for the “assist” actions of SRB, i.e. the mechanisms for SRB-assisted cracking must combine with the conventional SCC or CF mechanisms to fully illustrate the overall cracking process. To the best of our knowledge, this is a first-ever attempt to summarize the mechanisms of SRB-assisted cracking.

3.1 Theoretical interpretation of SRB-assisted cracking using the E-pH diagram

SRB-assisted cracking was confirmed via experiment and field studies. These results show that SRB-assisted cracking is a spontaneous process in the natural environment.

According to Wu et al., the driving forces of steel corrosion in an anaerobic near-neutral pH solution (ΔE_1) and under the plastic tensile stress (ΔE_2) can be, respectively, expressed as follows (Wu et al., 2018a):

$$\Delta E_1 = E_{H_2/H^+} - E_{Fe/Fe^{2+}} \quad (1)$$

$$\Delta E_2 = E_{H_2/H^+} - E_{Fe/Fe^{2+}} + \frac{\Delta PV_m}{zF} + \frac{n\Delta\tau R}{\alpha k N_{\max} zF} \quad (2)$$

where E_{H_2/H^+} and $E_{Fe/Fe^{2+}}$ are the equilibrium potentials for the oxidizations of H_2 and Fe, respectively. $\frac{\Delta PV_m}{zF}$ and

$\frac{n\Delta\tau R}{\alpha k N_{\max} zF}$ are the changes in electrode potential (ΔE^0) of iron under elastic and plastic stresses, respectively (Xu and Cheng, 2012). Given that they are positive under tensile stresses (Wu et al., 2016), ΔE_2 is bigger than ΔE_1 . TSteel corrosion is promoted by tensile stresses, and this is the thermodynamic reason for the stress-induced corrosion of steel.

When inoculated into the environment, SRB can obtain electrons by oxidizing organics, then reduce sulfates to sulfide organics, obtaining the energy for their physiological activity. Therefore, the driving forces of SRB-assisted corrosion (ΔE_3) and SRB-assisted cracking (ΔE_4) of steels can be, respectively, expressed as follows (Wu et al., 2018a):

$$\Delta E_3 = E_{HS^-/SO_4^{2-}} - E_{Fe/Fe^{2+}} \quad (3)$$

$$\Delta E_4 = E_{HS^-/SO_4^{2-}} - E_{Fe/Fe^{2+}} + \frac{\Delta PV_m}{zF} + \frac{n\Delta\tau R}{\alpha k N_{\max} zF} \quad (4)$$

where, $E_{HS^-/SO_4^{2-}}$ is the equilibrium potentials of the following equation (Sherar et al., 2011; Yuan et al., 2013):

It is obvious that ΔE_4 is bigger than ΔE_1 , ΔE_2 , and ΔE_3 . The fact indicates that applied stress and SRB's physiological activity synergistically increase the corrosion driving force and, hence, synergistically facilitate the steel corrosion. This is the thermodynamical interpretation of SRB-assisted cracking for Fe-based metal (Wu et al., 2018a). Although the thermodynamical interpretation was extracted from rigorous derivations, the role of biofilm in SRB-assisted cracking was neglected in the calculation of the cell potentials (Wu et al., 2018a), which may be one of the essential factors in steel cracking.

3.2 Pitting damage mechanism

By direct or indirect contact with the steel surface, SRB can obtain cathodic hydrogen and electrons from the steel to reduce sulfate to sulfide (Reguera et al., 2005; Yu et al., 2013), then facilitate the formation of pits on the steel surface. Besides, FeS-Fe microgalvanic couples may form under SRB biofilm, where iron played the role of the anode, and then induce pitting corrosion (Iverson, 1968). Furthermore, the biofilm was reported to be partial and porous, creating concentration gradients of pH, chloride (Sheng

et al., 2007), and sulfur. The steel surface are altered or influenced by this porous film, and some microcells even form on the steel surface (King and Miller, 1971), resulting in localized corrosion. Under the action of tensile stress, stress concentration will generate at pit tips, and the bottom of localized corrosion, thus, enhancing the local electrochemical activity of the metal. Then the localized corrosion rate increases, which can lead to steel cracking. This is the major reason why SRB assist in cracking. On the surface of a broken X52 steel, pits were laid on the fractured area, and it also can be found in the crack propagation path, and cracks were rightly initiated from the pit bottom (Abedi et al., 2007). Therefore, it could reasonably be inferred that the fracture failure was induced via the pitting corrosion damage mechanism.

Recently, Wu et al. investigated the corrosion behavior of an X80 steel under static elastic stress in the presence of SRB. In their experiment (Wu et al., 2014b), the applied elastic stress combining with the intrinsic growth stresses of the corrosion product (Bull, 1998) increases the porosity of the corrosion product film, and this even results into its partial falling. A large number of corrosion spots are spotted on the bared metal matrix. An interesting phenomenon is that some tiny secondary corrosion pits can be observed at the bottom of the primary pitting.

On the basis of the above results, the corrosion processes in the condition are restated here. (1) The activity of SRB and the increased porosity of the product film give rise to the localized corrosion. (2) Under the applied elastic stress, stress concentration generates at the bottoms of localized corrosion, increasing the corrosion rate of steel. (3) The activity and metabolite of SRB work again and induce the secondary corrosion pits at the bottom of the initial localized corrosion. Repetition of processes (2) and (3) may lead to successive pits; hence, the initiation of cracks under static load in the presence of SRB. In another experiment, Wu et al. observed the same phenomenon when the steel under the yield stress was exposed to the soil solution inoculated with SRB (Wu et al., 2014a). It was believed that the secondary/successive pits have the potential to be the core of an SRB-assisted cracking mechanism (Wu et al., 2014a).

3.3 Hydrogen damage mechanism

For an anaerobic solution, the cathodic reaction is the reduction of hydrogen ions or water, forming atomic hydrogen (H^0). A portion H^0 may combine to molecular hydrogen (H_2) and then escape from the electrolyte. However, some H^0 can absorb on the metal surface, enter

the metal lattice, segregate at micro-structural trap sites, diffuse to and enrich in the crack tip region and, thus, enhance crack propagation of the metal (Wu et al., 2015a). The hydrogen source depends on the environment chemistry (Turnbull, 1986). The factors affecting hydrogen uptake on the crack tip region is likely to induce crack initiation and alter crack propagation rate. For example, it is reported that a small amount of H_2S in chloride-containing solutions increased the hydrogen uptake and greatly enhanced fatigue crack rates (Iyer et al., 1990). The metabolic activity of SRB in anaerobic environments may affect the hydrogen production and uptake processes (de Romero et al., 2002, 2005; Lunarska et al., 2007; Domzalicki et al., 2008) and, hence, enhance crack propagation (Gangloff and Kelly, 1994; Robinson and Kilgallon, 1998; Javaherdashti et al., 2006; Domzalicki et al., 2007). As has been documented, the hydrogen uptakes into ferrite-pearlite and sorbite steels by the active SRB increased the environmental cracking rate and the SCC susceptibility in synthetic seawater and natural sea environment (Domzalicki et al., 2007, 2008; Lunarska et al., 2007).

SRB obtain the needed energy by reducing sulfate ions (SO_4^{2-}) and oxidizing organic molecules (von Wolzogen Kuhr and van der Vlugt, 1934):

From reaction (6), two opposite roles of the SRB in hydrogen evolution can be extracted. The first role is that SRB may remove H^0 from the metal surface, which can lower the H^0 concentration on the metal surface and suppresses the H^0 permeation into the metal, thus, reducing the danger of accelerated crack propagation. Although the remove action is the core of the widely accepted cathodic depolarization theory of MIC induced by SRB, it was denied by many researchers (Little et al., 2000; de Romero et al., 2002, 2005). De Romero et al. demonstrated that SRB do not generate and absorb permeable extracellular H^0 , as they organotrophically produce the H^0 needed to reduce sulfate to sulfide at the cell level, without no net H^0 production (de Romero et al., 2002, 2005):

Therefore, the remove role of SRB can be neglected in dealing with the relationship of hydrogen and SRB-assisted cracking.

The second role of SRB is releasing sulfur ions (S^{2-}) to the external environment. The S^{2-} combine with H^+ in solution forming H_2S and enhance the generation of

atomic hydrogen for the adsorption on the steel surface by reactions (8) (Edyvean, 1991; Gee and Chen, 1995; Eadie et al., 2005; Zucchi et al., 2006; Sowards et al., 2014) and (9) (Gee and Chen, 1995) and reduce the rate of hydrogen recombination according to reaction (10) (Robinson and Kilgallon, 1998):

Then, the adsorbed hydrogen (H_{ads}) enters into steels and diffuses to the plastic zone ahead of the cracks where stress triaxiality is high, causing embrittlement of steels. In this regard, SRB play a role analogous to hydrogen recombination poisons. The hydrogen damage mechanism is the most widely accepted mechanism for SRB-assisted cracking and was reviewed in detail for the SRB-assisted SCC/CF of high strength steels in marine environments by Robinson and Kilgallon (Robinson and Kilgallon, 1998).

In order to illuminate the roles of SRB on the hydrogen embrittlement (HE) of 690 steel in the marine environment, Robinson et al. measured the hydrogen concentration absorbed by steel (C_0) and K_{th} , and then proposed the relationship that existed between them (Robinson and Kilgallon, 1994). An inverse relationship was established between $\log K_{\text{th}}$ ($\text{MP}/\text{m}^{1/2}$) and C_0 (ppm) for both sterile and biologically active environments. The equation to the line is (Robinson and Kilgallon, 1994):

$$\log K_{\text{th}} = -C_0 + 1.6 \quad (11)$$

The applied cathodic potential and the SRB at the metal surface played a strong synergistic effect on the hydrogen permeation. The dependences of K_{th} on C_0 lies on the same straight line for both sterile and biologically active conditions. It is clear that the HE mechanism remains unchanged after the introduction of SRB into the system. The same phenomenon was recorded in the literature (Wu et al., 2015b) where SSRT were conducted to investigate the SCC susceptibility of X80 steel subjected to cathodic potentials exposed to the sterile and SRB-inoculated soil solution (Wu et al., 2015b). Area reduction (RA) was used to represent SCC susceptibility. A linear relationship between $\text{RA}/\text{RA}^{\text{air}}$ and C_0 (ppm) in double logarithmic coordinate was obtained for the steel (Figure 1). The equation to the line is expressed as follows (Wu et al., 2015b):

Figure 1: Effect of the absorbed hydrogen concentration (C_0) on the reduction in area (RA) for the X80 steel as tested in the sterile and inoculated soil solution (reproduced from Wu et al., 2015b with permission from the Editorial Office of Journal of Materials Science and Technology). A linear relationship between $\text{RA}/\text{RA}^{\text{air}}$ and C_0 in double logarithmic coordinate was obtained for the steel (as expressed in the figure). The dependences of $\lg(\text{RA}/\text{RA}^{\text{air}})$ on $\lg C_0$ lies on the same straight line for both the sterile and SRB-inoculated conditions. It is clear that the SCC mechanism remained unchanged after the introduction of SRB into the system.

$$\log(\text{RA}/\text{RA}^{\text{air}}) = -0.1238 \log(C_0) - 0.3386 \quad (12)$$

For the practical use of the fracture mechanisms, the K_{th} against C_0 relationship was used to calculate the applied stress required to propagate the certain length flaw. The cathodic potentials corresponding to these K_{th} values can be used to give a plot of applied stress against applied cathodic potential (Robinson and Kilgallon, 1998). Their results showed that there is a stress-potential region where crack propagate only takes place in the biologically active environment rather than in the sterile environment (Robinson and Kilgallon, 1998). It is obvious that this region gives prominence to the roles of SRB in the SCC of steels. The similar failure/safety diagram comparing the susceptibility of X80 and cathodic potentials was proposed in the literature (Wu et al., 2015b). In their work, reaction (12) was used in the selection of safe CP potentials in the presence of SRB in the soil environment (Figure 2). To eliminate the SRB effect on the SCC susceptibility of pipeline steel, the CP potential arranged in SRB-containing environment must be changed to $[-876 \text{ mV}, -943 \text{ mV}]$ from $[-776 \text{ mV}, -1020 \text{ mV}]$ in sterile environment. The selectable range of CP potentials in the SRB-containing environment is narrower than that in the sterile condition.

Another case for hydrogen damage mechanism is a recent report about the fatigue crack propagation of

Figure 2: Failure/safety diagram for the X80 pipeline steel in the sterile and SRB-inoculated soil solutions (reproduced from Wu et al., 2015b with permission from the Editorial Office of Journal of Materials Science and Technology). Under the requisition that the SCC susceptibility of pipeline steel is below 50%, the CP potential ranges in sterile and SRB-containing environments are [−776 mV, −1020 mV] and [−876 mV, −943 mV], respectively. The selectable range of CP potentials in the SRB-containing environment is narrower than that in the sterile condition.

X70 steel in SRB-inoculated ethanol solutions and in saltwater with applied cathodic potential (Sowards et al., 2014). The SRB-inoculated and cathodic-applied environments resulted in a typical crack propagation behavior that was characterized by (1) a steep increase in crack propagation rate at low ΔK followed by (2) a plateau region of ΔK -independent crack propagation rate across the intermediate values of ΔK . The dataset at $-1.03 \text{ V}_{\text{vs. SCE}}$ provided an environment where the test specimen was cathodically charged with abiotic hydrogen. The SRB data here coincided very well with the abiotic source of hydrogen, although the crack propagation rates were higher in the latter case. The SRB metabolism reduced the recombination of atomic hydrogen, increased the surface coverage, and promoted its absorption by the metal, providing a hydrogen source. The hydrogen damage mechanism is the main failure mode of SRB-assisted cracking.

3.4 Electrochemical model of SRB-assisted cracking

The chemical and electrochemical conditions at the tip of a crack govern the crack propagation process in corrosive media together with strain-stress conditions (Peng et al., 2003). Slobodyan et al. studied the effect of SRB on the electrochemical condition at the tips of stationary

and growing CF cracks in the Postage medium in the 1990s (Ratych and Slobodyan, 1986; Slobodyan et al., 1993). They corroborated that the metabolism of SRB significantly altered the electrochemical characteristics and intensified the electrochemical process at the tips of a static-load crack and a cyclic-loaded propagating crack. It was also reported that the presence of SRB reduced the efficacy of a Nefgan inhibitor (Slobodyan et al., 1993). On the basis of the experimental data and theoretical analysis, Serednyts'kyi found that the electrochemical process at the tip of a corrosion-fatigue crack in the presence of SRB underwent three stages and, hence, established the electrochemical mechanism of the process (Serednyts'kyi, 1997). In the present section, we draw the mechanism schematics according to their work (Figure 3) (Slobodyan et al., 1993; Serednyts'kyi, 1997) and illustrate the mechanism in detail as follows:

Stage 1: As shown in Slobodyan and coworkers' results (Slobodyan et al., 1993), during the first stage, the kinetic curves of the pH value vs. time for the tips of arrested and propagating cracks are located in the alkaline zone. The phenomenon can be explained by an increase in the concentration of OH^- due to the reaction of oxygen depolarization:

As the concentration of active OH^- at the crack tip increases as shown by reaction (13), the main anodic process may be reactions (14) and (15):

In the first stage of the process, the reactions of cathodic depolarization of oxygen and the anodic dissolution of iron at the tip are prevailing as shown in Figure 3A.

Stage 2: When oxygen was completely exhausted in the first stage, the cathodic reactions changed into the catalytic dissociation of water molecules on the active surface of the stressed metal at the crack tip:

Then, the activities of SRB accordingly increased and, hence, functioned in the corrosion process (Figure 3B). The main role of SRB in the corrosion process can be described as the removal of H^0 from the cathodic sections of the metal surface and the production of sulfide ions (reaction (6)).

Figure 3: Electrochemical modes of the corrosion process of a cracking tip in the presence of SRB (Slobodyan et al., 1993; Serednyts'kyi, 1997). In stage 1, the reactions of cathodic depolarization of oxygen and the anodic dissolution of iron at the tip are prevailing. The main reactions in stage 2 are the catalytic dissociation of water on the active surface of the metal followed by the discharge of hydrogen ions, the depolarization of hydrogen from the metal, and the increased anodic dissolution of iron. Stage 3 is characterized by the precipitation of corrosion products on the steel surface, the FeS-Fe microgalvanic couples, and the pits related to pit-failure mechanism.

Under the metabolism of SRB, the corrosion process was stimulated via reaction (6) as the reaction consumed the cathodic hydrogen produced by reaction (16).

The main reactions in the second stage are (1) the catalytic dissociation of water on the active surface of the metal followed by the discharge of hydrogen ions, (2) the depolarization of hydrogen from the metal, and (3) the increased anodic dissolution of iron.

Stage 3: The third stage of the corrosion process at the tip of a crack in the presence of SRB depended on the accumulation of insoluble and difficult soluble corrosion products. As ferrous sulfide is insoluble (Jones and Amy, 2002), the steel surface is shielded by its films. The formation of the film is conducive to protect the metal against corrosion as it inhibited the interaction of steel with media. However, when SRB were involved

in it, the corrosion rate increases (from $20 \mu\text{m years}^{-1}$ to $120 \mu\text{m years}^{-1}$). Most probably, SRB decreased the density of the protective films of ferrous sulfide. The effect provided favorable conditions for the formation of FeS-Fe microgalvanic couples, in which iron played the role of the anode and, then, induced pitting on the steel surface and, hence, resulted into corrosion fracture according to the pitting damage mechanism (Figure 3C). In short, the third stage is characterized by the precipitation of corrosion products on the steel surface and the FeS-Fe microgalvanic couples.

Based on the cathodic depolarization theory (although it is controversial (de Romero et al., 2002, 2005)), the model was extracted from the electrochemical parameters obtained at the tip of the crack. To some extent, it correlated with the data of inspections of the main pipelines in

soils with elevated corrosive and microbiological activity (Serednitskii et al., 1988).

The above hydrogen damage mechanism and electrochemical model are based on the existing cracks on the steel surface. In other words, these mechanisms may become inoperative in the prediction of crack initiation induced by SRB, which is the chief shortcoming of the two mechanisms.

3.5 Additional comment on damage mechanism

Although the above mechanisms provide relatively comprehensive understandings for the SRB-assisted cracking, an additional comment on sulfide must be drawn here on damage mechanisms.

The effect of sulfur-containing compounds near the metal surface (Lee et al., 1993) can be not over-emphasized in SRB-assisted cracking. Three main roles were present in the above mechanisms: (1) the effect on hydrogen entry into steel (Domzalicki et al., 2008; Biezma, 2011), (2) the high conductivity to transfer electrons from the steel to the corrosion product (Little et al., 2000), (3) the formation of Fe-FeS microgalvanic couples (Singh Raman, 2003; Kakooei et al., 2012). Surprisingly, Arilahti et al. recorded a freak phenomenon where sulfide diffused into the grain boundaries ahead of the crack tip in a copper alloy in groundwater containing S^{2-} (Arilahti et al., 2011), which suggested that the stress-strain field ahead of the crack tip drove the sulfur ingress into the copper alloy. It may be of significance to clarify whether the internal diffusion of sulfide exists in steel under a stress-strain field, for the mechanism in sight of SRB-assisted cracking of steels. Furthermore, the role of biofilm may be an important factor for SRB-assisted cracking. As was reported that gradients of pH, chloride, and sulfur can be created under the biofilm (Sheng et al., 2007). Therefore, more attention should be paid to the essential roles of sulfide and biofilm in SRB-assisted cracking.

4 Factors affecting SRB-assisted cracking

4.1 SRB physiological activation

During the biofilm formation, SRB experience different physiological stages, including attachment, maturation, and dispersion (Sauer et al., 2002). This means that the

SRB cell count as well as their metabolite in the biofilm will change in different physiological stages, and hence, the local environment around the steel surface may change accordingly. The environment change could alter the cracking behavior of the steel; thus, the SRB physiological activation is one of the factors affecting SRB-assisted cracking.

Wu et al. found that SRB increase the SCC susceptibility and brings about the additional features of quasi-cleavage in the primeval ductile fracture morphology, and demonstrated that SRB displays the most noticeable impact during the maturation stage (Wu et al., 2015b). The fact is in accord with the results in the study of Beech et al., in which they found that the MIC risk maybe more directly related to the metabolic state and rate than the number of microbial cells (Beech and Sunner, 2007). Furthermore, the amount of active SRB was proven to greatly affect hydrogen permeation (Wang et al., 2017b) and the SCC process (Wang et al., 2017a) of X80 steel. In the maturation stage, the maximal cell quantity results in the strongest effect on hydrogen permeation (Wang et al., 2017b), bringing about the most serious SCC susceptibility (Wang et al., 2017a).

In order to reveal the SRB effect on cracking, maintaining its relatively high physiological activity and preventing the biological contamination is an issue of great importance during the laboratory experiments. Cracking of metal in natural environment is an extremely slow process; thus, the laboratory and field researches on SRB-assisted cracking are time consuming. In a closed system, SRB count and physiological activity will change with time. Therefore, it is necessary to take appropriate measures to support the growth of SRB during the experiments. Recently, Wu et al. made a beneficial attempt in this point by renewing the experimental medium using the peristaltic pump and by maintaining the experimental temperature using the thermostatic water bath. In this way, the SRB count and physiological activity are kept in a constantly high level during the 3-month experiments. What is more, to study the SRB-assisted cracking process, applying the static or dynamic stresses on the specimen is necessary and so is keeping the anaerobic condition and the experimental temperature. Thus, the experimental setup as well as the experimental procedure may become completely complex. The risk of biological contamination increases accordingly. It was reported that mixed microorganisms can change the local environment and the corrosion process of metals. Therefore, sterilizing undesired microorganisms will be a new issue worthy of our attention for the study of SRB-assisted cracking.

4.2 Biogenic H_2S

When the abiotic H_2S is introduced into a system, it can react with water to release protons for cathodic reduction of steel corrosion (reaction (1a)). SRB can produce biogenic HS^- (reaction (5)) or S^{2-} (reaction (6)). Then, the HS^- or S^{2-} can consume protons to form biogenic H_2S . Obviously, the abiotic and biogenic H_2S are likely to play different roles in steel corrosion (de Mele et al., 1991; Duque, 2007). H_2S at over 2000 ppm can be produced by bacteria under optimum experimental conditions (Thomas et al., 1987). Therefore, biogenic H_2S is an important factor in SRB-assisted cracking.

In the electrochemical model of SRB-assisted cracking (Section 3.4) (Serednyts'kyi, 1997), the biogenic H_2S react with Fe^{2+} to form FeS , which is the necessary prerequisite for the FeS - Fe microgalvanic couples. The biogenic H_2S is rightly the poisoner of the combination of hydrogen atoms to the gaseous molecule, thus, making more hydrogen available for embrittlement (Wu et al., 2015a,b). This is the core of the hydrogen damage mechanism (Section 3.3). From the two mechanisms, the biogenic H_2S plays a positive role in SRB-assisted cracking. Thomas et al. found that crack propagation rates in seawater containing biogenic H_2S increased significantly for RQT 701 and 501 steels, and ΔK_{th} were reduced to a smaller value found in seawater (Thomas et al., 1987). Also, the effects were enhanced with the increase in biogenic H_2S levels, as the H_2S can overcome the crack tip blunting effect (Thomas et al., 1987). Furthermore, the effects of lower levels of biogenic and abiotic H_2S were very similar, but the higher levels of abiotic H_2S have a much greater effect on crack propagation than biogenic H_2S (Thomas et al., 1987).

4.3 Acidity

Soil pH is one of the abiotic factors that affect the steel corrosion rate, and the diversity and distribution of microbial species in a region (Fierer and Jackson, 2006). Neutral pH soil harbors the most diverse communities, while acidic pH soil only tolerates the least diverse communities. On the other hand, the negatively charged organic matter in EPS can bind metal cations, leading to the changes in pH of the local environment (Beech and Cheung, 1995).

To our knowledge, no prior researches have focused on the effect of pH on SRB-assisted cracking. However, some useful conclusions can be extracted by comparing the results in the different literature. The X80 steel displayed the highest SRB-assisted cracking susceptibility

in a neutral pH soil solution after pre-incubation of 3 days (Wu et al., 2015b), but after pre-incubation of 8 days in the acid soil environment (Wang et al., 2017a). This may stem from the SRB physiological activation, as discussed in Section 4.1. Furthermore, the RAs during SSRT in the neutral pH soil solution were always larger than those in the acid soil environment, while almost the same effects of SRB on the RA decrease were observed in the two soil solutions (Wu et al., 2015b; Wang et al., 2017a). As the maximum SRB numbers are, respectively, about 1.4×10^3 and 2×10^7 cells/ml in the acid and neutral pH solutions, it is reasonable to ratiocinate that a single sulfate-reducing bacterium may play a more prominent role in the acid solution. In this solution, HS^- biologically secreted by SRB are more likely to combine with protons to form biogenic H_2S , increasing the hydrogen permeation and then bringing about more quasi-cleavage features in the ductile morphology (Wu et al., 2015b; Wang et al., 2017a).

4.4 Applied stress

The cracking process of materials is invariably dominated by the simultaneous actions of themselves, conducive environment, and applied stress. SRB-assisted cracking of pipeline steel is promoted by the applied stresses (Wu et al., 2018b). The corrosion rate (R_p^{-1}) of X80 steel under different level stresses in sterile and SRB-inoculated soil solutions after immersion for 60 days were extracted from the literature (Wu et al., 2014a,b), as shown in Figure 4. It is evident that the SRB activity and the applied stresses display the profound synergistic effects on corrosion of steel in the soil environment and that their synergistic effects become more apparent under the greater stresses. Under the synergistic effects, the secondary pitting on the bottom of wide shallow pits generates on steel surface (Wu et al., 2014b), which provides supporting evidence for the pitting damage mechanism.

As for dynamic load, the physiological activity of SRB was reported to bring about the decrease in fatigue life (Huang, 2004) and the additional increase in fatigue crack propagation rates (Sowards et al., 2014), in comparison with those in sterile environments. Furthermore, the fatigue crack propagation rates of steel increased with the ΔK increase in SRB-inoculated environment, and the SRB-assisted fracture morphologies varied depending on ΔK . Low values of ΔK resulted in a predominantly intergranular fracture, whereas intermediate and high values of ΔK resulted in a transgranular fracture mode (Sowards et al., 2014).

Figure 4: A summary of corrosion rate (R_p) of X80 steel under different level stresses in sterile and SRB-inoculated soil solutions after immersion for 60 days (Wu et al., 2014a,b). The specimens under different level stresses are named the specimen S_0 ($0.0 \sigma_{0.2}$), $S_{0.75}$ ($0.75 \sigma_{0.2}$), and $S_{1.0}$ ($1.0 \sigma_{0.2}$), respectively.

4.5 Cathodic protection potential

In reality, CP is one of the most commonly used methods to decrease the corrosion rate of steels in soil and water environments. For pipeline steel, the referred upper CP potentials in soil with and without SRB are -876 and -776 mV vs. SCE, respectively. Under CP, the anodic reactions of steel are inhibited, while the cathodic reactions are promoted, which means that more cathodic protons may generate on the steel surface. As discussed in Section 3.3, the generation of cathodic protons is the necessary prerequisite to the hydrogen damage mechanism during SRB-assisted cracking. So, CP and SRB may be likely to play a synergistic effect on the hydrogen permeation and the subsequent cracking process. Therefore, the effects of CP on SRB-assisted cracking are worthy of much attention.

The SCC susceptibility of X80 steel under the combined effects of CP and SRB were studied in the literature (Wu et al., 2015b). SRB plays a positive role in increasing the SCC susceptibility of steel, and the SCC susceptibility increases with a decrease in the applied CP potentials in the potential range $[-725 \text{ mV}, -1176 \text{ mV}]$ (Wu et al., 2015b). The physiological activity of SRB and CP synergistically promotes the SCC processes of steel in the soil environment, while the synergistic action becomes limited with a decrease in the cathodic potential (Wu et al., 2015b). Domzalicki et al. also documented that the presence of SRB promotes the SCC susceptibility, being especially pronounced at potentials -1100 mV vs. SCE to -1200 mV vs. SCE (Domzalicki et al., 2007). At lower CP potentials, the SCC susceptibility in SRB-inoculated and sterile solutions equalizes (Domzalicki et al., 2007). The alkalinization of solutions due to lower CP potentials (Wu et al.,

2015b) and the corresponding suppression of SRB growth (Domzalicki et al., 2007) are responsible for the decline in their synergistic action. Furthermore, the CP was reported to decrease the SCC K_{th} of the 500 and 690 steels in SRB-inoculated marine environment (Robinson and Kilgallon, 1994), and it can increase the fatigue crack propagation rates of SE500 steel under the same ΔK in SRB-inoculated seawater (Robinson and Kilgallon, 1998).

4.6 Electron uptake from iron

Based on the two distinct types of anaerobic metabolisms, namely, respiration and fermentation, Xu et al. classified most anaerobic MIC attacks into two basic types (Xu et al., 2013, 2016). Type I MIC involves microorganisms that perform anaerobic respiration, while Type II MIC involves secreted corrosive metabolites such as organic acids. SRB respiration typically uses sulfate and organic carbons as the terminal electron acceptor and donors, respectively (Jia et al., 2018); thus, most SRB MIC attacks is attributed to Type I MIC. However, in the absence of organic carbon, Fe^0 can be an electron donor for energy production in order to survive energy deprivation of SRB (Xu and Gu, 2014) by direct or mediated electron transfer (Venzlaff et al., 2013; Zhang et al., 2015). As a consequence, an additional corrosion micro-cell circuit, including a cathode (bacterium), an anode (steel surface), electron mediators (i.e. nanowire (Sherar et al., 2011) and riboflavin (Zhang et al., 2015)), and ionic mediator (solution), is likely to generate in the SRB-inoculated system, which may enhance the anodic process. Besides, the synergistic effect between anodic dissolution and HE is recommended to illustrate the near-neutral pH SCC of pipeline steels in deoxygenated soil

solutions (Chen et al., 2007; Eslami et al., 2011). Therefore, it is reasonable to suppose that the electron uptake from iron by SRB is likely to play an important role in the SRB-assisted cracking process. A well-designed experiment is imperative to illuminate the role. It seems likely that many surprises (or mysteries) are stored in it.

5 Conclusion

In the paper, a mini-review is given for the available information on SRB-assisted cracking. SRB-assisted SCC/CF of steels was regularly reviewed. The thermodynamic interpretation and possible mechanisms are summarized in detail. The factors affecting SRB-assisted cracking are also discussed in this paper.

From the discussion above, more attention should be paid to the potential roles of sulfide and biofilm in the process of SRB-assisted cracking. Furthermore, electron uptake from iron by SRB is a new area for the research of SRB-assisted cracking, and further surprises are likely to be in store.

Abbreviations

MIC	microbiologically influenced corrosion
SRB	sulfate-reducing bacteria
NRB	nitrate-reducing bacteria
APB	acid-producing bacteria
SCC	stress corrosion cracking
CF	corrosion fatigue
SSRT	slow strain rate testing
HE	hydrogen embrittlement
RA	area reduction
SCE	saturated calomel electrode
CP	cathodic protection

Symbols

K_{th}	threshold stress intensity factor
ΔK	stress intensity factor amplitude
ΔK_{th}	threshold stress intensity factor amplitude
E	equilibrium potential of the electrode reaction
ΔE^0	change in electrode potential
ΔE_e^0	change in electrode potential under elastic stress
ΔE_p^0	change in electrode potential under plastic stress
ΔE	cell potential between the cathodic and anodic reactions
p_{H_2}	partial pressure for H_2 (in bar)

z	stoichiometric coefficient of electrons in electrode reaction
F	Faraday's number
ΔP	additional elastic stress on metal
V_m	molar volume of the iron
n	number of dislocation in a dislocation pile-up
k	Boltzmann constant
R	ideal gas constant
N_{max}	maximum dislocation density
H_{ads}	adsorbed hydrogen
H^0	atomic hydrogen
C_0	hydrogen concentration of absorbed by steel

Greek characters

α	proportionality coefficient in linear dependence of dislocation density on plastic strain
$\Delta\tau$	hardening intensity

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References

- Abedi SS, Abdolmaleki A, Adibi N. Failure analysis of SCC and SRB induced cracking of a transmission oil products pipeline. *Eng Fail Anal* 2007; 14: 250–261.
- Al-Nabulsi KM, Al-Abbas FM, Rizk TY, Salameh AaEM. Microbiologically assisted stress corrosion cracking in the presence of nitrate reducing bacteria. *Eng Fail Anal* 2015; 58: 165–172.
- Ariilahti E, Lehtikuusi T, Olin M, Saario T, Varis P. Evidence for internal diffusion of sulphide from groundwater into grain boundaries ahead of crack tip in Cu OFP copper. *Corros Eng Sci Technol* 2011; 46: 134–137.
- Beech IB, Cheung CWS. Interactions of exopolymers produced by sulphate-reducing bacteria with metal ions. *Int Biodeterior Biodegrad* 1995; 35: 59–72.
- Beech IB, Gaylarde CC. Recent advances in the study of biocorrosion. *Rev Microbiol* 1999; 30: 177–190.
- Beech IB, Sunner JA. *Sulphate-reducing bacteria: environmental and engineered systems*. Cambridge: Cambridge University Press, 2007.

- Biezma MV. The role of hydrogen in microbiologically influenced corrosion and stress corrosion cracking. *Int J Hydrogen Energy* 2011; 26: 515–520.
- Bull SJ. Modeling of residual stress in oxide scales. *Oxid Met* 1998; 49: 1–17.
- Chen W, Van Boven G, Rogge R. The role of residual stress in neutral pH stress corrosion cracking of pipeline steels – part II: Crack dormancy. *Acta Mater* 2007; 55: 43–53.
- de Mele MFL, Moreno DA, Ibars JR, Videla HA. Effect of inorganic and biogenic sulfide on localized corrosion of heat-treated type 304 stainless steel. *Corrosion* 1991; 47: 24–30.
- de Romero MF, Duque Z, de Rincon OT, Perez O, Araujo I, Briceno B. Microbiological corrosion: Hydrogen permeation and sulfate-reducing bacteria. *Corrosion* 2002; 58: 429–435.
- de Romero M, Duque Z, Rodriguez L, de Rincon O, Perez O, Araujo I. A study of microbiologically induced corrosion by sulfate-reducing bacteria on carbon steel using hydrogen permeation. *Corrosion* 2005; 61: 68–75.
- Domzalicki P, Lunarska E, Birn J. Effect of cathodic polarization and sulfate reducing bacteria on mechanical properties of different steels in synthetic sea water. *Mater Corros* 2007; 58: 413–421.
- Domzalicki P, Birn J, Lunarska E. Hydrogen permeation measurements in natural sea environment. *Mater Corros* 2008; 59: 732–738.
- Duan J, Wu S, Zhang X, Huang G, Du M, Hou B. Corrosion of carbon steel influenced by anaerobic biofilm in natural seawater. *Electrochim Acta* 2008; 54: 22–28.
- Duque Z. A review of corrosion by biogenic sulphide in the oil industry. *Rev Tec Fac Ing Univ Zulia* 2007; 30: 146–156.
- Eadie RL, Szklarz KE, Sutherby RL. Corrosion fatigue and near-neutral pH stress corrosion cracking of pipeline steel and the effect of hydrogen sulfide. *Corrosion* 2005; 61: 167–173.
- Edyvean RGJ. Hydrogen sulphide: a corrosive metabolite. *Int Biodeterior* 1991; 27: 109–120.
- Egbewande A, Chen W, Eadie R, Kania R, Van Boven G, Worthingham R, Been J. Transgranular crack growth in the pipeline steels exposed to near-neutral pH soil aqueous solutions: discontinuous crack growth mechanism. *Corros Sci* 2014; 83: 343–354.
- Eslami A, Kania R, Worthingham B, Boven GV, Eadie R, Chen W. Effect of CO₂ and R-ratio on near-neutral pH stress corrosion cracking initiation under a disbonded coating of pipeline steel. *Corros Sci* 2011; 53: 2318–2327.
- Fang BY, Han EH, Wang JQ, Ke W. Influence of strain rate on near-neutral pH environmentally assisted cracking of pipeline steels. *Acta Metall Sin* 2005; 41: 1174–1182.
- Fang BY, Han EH, Wang JQ, Zhu ZY, Ke W. Hydrogen in stress corrosion cracking of X-70 pipeline steels in near-neutral pH solutions. *J Mater Sci* 2006; 41: 1797–1803.
- Fierer N, Jackson RB. The diversity and biogeography of soil bacterial communities. *Proc Natl Acad Sci USA* 2006; 103: 626–631.
- Gangloff RP, Kelly RG. Microbe-enhanced environmental fatigue crack propagation in HY130 steel. *Corrosion* 1994; 50: 345–354.
- Gee R, Chen ZY. Hydrogen embrittlement during the corrosion of steel by wet elemental sulphur. *Corros Sci* 1995; 37: 2003–2011.
- Huang Y. Corrosion failure of marine steel in sea-mud containing sulfate reducing bacteria. *Mater Corros* 2004; 55: 124–127.
- Huang Y, Zhou E, Jiang C, Jia R, Liu S, Xu D, Gu T, Wang F. Endogenous phenazine-1-carboxamide encoding gene PhzH regulated the extracellular electron transfer in biocorrosion of stainless steel by marine *Pseudomonas aeruginosa*. *Electrochem Commun* 2018; 94: 9–13.
- Iverson WP. Corrosion of iron and formation of iron phosphide by *Desulfovibrio desulfuricans*. *Nature* 1968; 217: 1265–1267.
- Iyer RN, Takeuchi I, Zamanzadeh M, Pickering HW. Hydrogen sulfide effect on hydrogen entry into iron: a mechanistic study. *Corrosion* 1990; 46: 460–468.
- Javaherdashti R. Microbiologically influenced corrosion: an engineering insight. London: Springer, 2008.
- Javaherdashti R. Impact of sulphate-reducing bacteria on the performance of engineering materials. *Appl Microbiol Biotechnol* 2011; 92: 1507–1517.
- Javaherdashti R, SinghRaman RK, Panter C, Pereloma EV. Microbiologically assisted stress corrosion cracking of carbon steel in mixed and pure cultures of sulfate reducing bacteria. *Int Biodeterior Biodegrad* 2006; 58: 27–35.
- Javaherdashti R, Nwaoha C, Ebenso EE. Fuzzy prediction of corrosion resistance of duplex stainless steel to biotic iron reducing bacteria and abiotic synthetic seawater environments: a phenomenological approach towards a multidisciplinary concept. *Int J Electrochem Sci* 2012; 7: 12573–12586.
- Jia R, Yang D, Xu J, Xu D, Gu T. Microbiologically influenced corrosion of C1018 carbon steel by nitrate reducing *Pseudomonas aeruginosa* biofilm under organic carbon starvation. *Corros Sci* 2017; 127: 1–9.
- Jia R, Tan JL, Jin P, Blackwood DJ, Xu D, Gu T. Effects of biogenic H₂S on the microbiologically influenced corrosion of C1018 carbon steel by sulfate reducing *Desulfovibrio vulgaris* biofilm. *Corros Sci* 2018; 130: 1–11.
- Jones DA, Amy PS. A thermodynamic interpretation of microbiologically influenced corrosion. *Corrosion* 2002; 58: 638–645.
- Kakooei S, Ismail MC, Ariwahioedi B. Mechanisms of microbiologically influenced corrosion: a review. *World Appl Sci J* 2012; 17: 524–531.
- Kholodenko VP, Jigletsova SK, Chugunov VA, Rodin VB, Kobelev VS, Karpov SV. Chemicomicrobiological diagnostics of stress corrosion cracking of trunk pipelines. *Appl Biochem Microbiol* 2000; 36: 594–601.
- King RA, Miller JDA. Corrosion by sulphate-reducing bacteria. *Nature* 1971; 233: 491–492.
- Lee W, Lewandowski Z, Morrison M, Characklis WG, Avci R, Nielsen PH. Corrosion of mild steel underneath aerobic biofilms containing sulfate-reducing bacteria part II: at high bulk oxygen concentration. *Biofouling* 1993; 7: 217–239.
- Li H, Yang C, Zhou E, Yang C, Feng H, Jiang Z, Xu D, Gu T, Yang K. Microbiologically influenced corrosion behavior of S32654 super austenitic stainless steel in the presence of marine *Pseudomonas aeruginosa* biofilm. *J Mater Sci Technol* 2017; 33: 1596–1603.
- Li Y, Xu D, Chen C, Li X, Jia R, Zhang D, Sand W, Wang F, Gu T. Anaerobic microbiologically influenced corrosion mechanisms interpreted using bioenergetics and bioelectrochemistry: a review. *J Mater Sci Technol* 2018; 34: 1713–1718.
- Little BJ, Ray RI, Pope RK. Relationship between corrosion and the biological sulfur cycle: a review. *Corrosion* 2000; 56: 433–443.
- Little B, Staehle R, Davis R. Fungal influenced corrosion of post-tensioned cables. *Int Biodeterior Biodegrad* 2001; 47: 71–77.

- Little BJ, Lee JS, Ray RI. Diagnosing microbiologically influenced corrosion: a state-of-the-art review. *Corrosion* 2006; 62: 1006–1017.
- Liu H, Gu T, Asif M, Zhang G, Liu H. The corrosion behavior and mechanism of carbon steel induced by extracellular polymeric substances of iron-oxidizing bacteria. *Corros Sci* 2017; 114: 102–111.
- Liu H, Gu T, Zhang G, Liu H, Cheng YF. Corrosion of X80 pipeline steel under sulfate-reducing bacterium biofilms in simulated CO₂-saturated oilfield produced water with carbon source starvation. *Corros Sci* 2018a; 136: 47–59.
- Liu H, Zhong X, Liu H, Frank Cheng Y. Microbiologically-enhanced galvanic corrosion of the steel beneath a deposit in simulated oilfield-produced water containing *Desulfotomaculum nigrificans*. *Electrochem Commun* 2018b; 90: 1–5.
- Lu BT, Luo JL, Norton PR, Ma HY. Effects of dissolved hydrogen and elastic and plastic deformation on active dissolution of pipeline steel in anaerobic groundwater of near-neutral pH. *Acta Mater* 2009; 57: 41–49.
- Lunarska E, Birn J, Domzalicki P. Hydrogen uptake by structural steels at cathodic protection in sea water inoculated with sulfate reducing bacteria. *Mater Corros* 2007; 58: 13–19.
- Maruthamuthu S, Kumar BD, Ramachandran S, Anandkumar B, Paanichamy S, Chandrasekaran M, Subramanian P, Palaniswamy N. Microbial corrosion in petroleum product transporting pipelines. *Ind Eng Chem Res* 2011; 50: 8006–8015.
- Mehta HS, Gosselin SR. Environmental factor approach to account for water effects in pressure vessel and piping fatigue evaluations. *Nucl Eng Des* 1998; 181: 175–197.
- Oskuie AA, Shahrabi T, Shahriari A, Saebnoori E. Electrochemical impedance spectroscopy analysis of X70 pipeline steel stress corrosion cracking in high pH carbonate solution. *Corros Sci* 2012; 61: 111–122.
- Peng QJ, Li GF, Shoji T. The crack tip solution chemistry in sensitized stainless steel in simulated boiling water reactor water studied using a microsampling technique. *J Nucl Sci Technol* 2003; 40: 397–404.
- Puiggali M, Roussier S, Touzet M. Fatigue crack initiation on low-carbon steel pipes in a near-neutral-pH environment under potential control conditions. *Corrosion* 2002; 58: 961–970.
- Qian H, Xu D, Du C, Zhang D, Li X, Huang L, Deng L, Tu Y, Molc JMC, Terrynd HA. Dual-action smart coatings with a self-healing superhydrophobic surface and anti-corrosion properties. *J Mater Chem A* 2017; 5: 2355–2364.
- Raman RKS, Javaherdashti R, Panter C, Pereloma EV. Hydrogen embrittlement of a low carbon steel during slow strain testing in chloride solutions containing sulphate reducing bacteria. *Mater Sci Technol* 2005; 21: 1094–1098.
- Rao TS, Nair KVK. Microbiologically influenced stress corrosion cracking failure of admiralty brass condenser tubes in a nuclear power plant cooled by freshwater. *Corros Sci* 1998; 40: 1821–1836.
- Ratych LV, Slobodyan IM. Effect of inhibitors on the electrochemical conditions at the crack tip in cyclic loading 40 Kh steel. *Fiz-Khim Mekh Mater* 1986; 22: 68–75.
- Reguera G, McCarthy KD, Mehta T, Nicoll JS, Tuominen MT, Lovley DR. Extracellular electron transfer via microbial nanowires. *Nature* 2005; 435: 1098–1101.
- Rizk TY, Al-Nabulsi KM, Cho MH. Microbially induced rupture of a heat exchanger shell. *Eng Fail Anal* 2017; 76: 1–9.
- Robinson MJ, Kilgallon PJ. Hydrogen embrittlement of cathodically protected high-strength, low-alloy steels exposed to sulfate-reducing bacteria. *Corrosion* 1994; 50: 626–635.
- Robinson MJ, Kilgallon PJ. A review of the effects of sulfate reducing bacteria in the marine environment on the corrosion fatigue and hydrogen embrittlement of high strength steels. Health and Safety Executive – Offshore Technology Report 1998; 1–29.
- Sauer K, Camper AK, Ehrlich GD, Costerton JW, Davies DG. *Pseudomonas aeruginosa* displays multiple phenotypes during development as a biofilm. *J Bacteriol* 2002; 4: 1140–1154.
- Serednitskii YA, Suprun VV, Bodak VS, Kopteva ZP, Zanina VV, Kozlova IA, Dombrovskii BO. Microbiological corrosion of steel pipelines and mastic insulating coatings. *Sov Mater Sci* 1988; 24: 419–424.
- Serednits'kyi YA. Mechanism of corrosion of 40 KH steel near a crack tip in the presence of sulfate-reducing bacteria. *Mater Sci* 1997; 33: 29–34.
- Sheng X, Ting YP, Pehkonen SO. The influence of sulphate-reducing bacteria biofilm on the corrosion of stainless steel AISI 316. *Corros Sci* 2007; 49: 2159–2176.
- Sherar BWA, Power IM, Keech PG, Mitlin S, Southam G, Shoesmith DW. Characterizing the effect of carbon steel exposure in sulfide containing solutions to microbially induced corrosion. *Corros Sci* 2011; 53: 955–960.
- Singh Raman RK. Interplay of microbiological corrosion and alloy microstructure in stress corrosion cracking of weldments of advanced stainless steels. *Sadhana – Acad P Eng S* 2003; 28: 467–473.
- Slobodyan IM, Bodak VS, Serednits'kyi YA, Ratych LV, Antonovs'ka NS. Effect of sulfate-reducing bacteria on the electrochemical conditions at a crack tip. *Mater Sci* 1993; 29: 507–513.
- Sowards JW, Williamson CHD, Weeks TS, McColskey JD, Spear JR. The effect of *Acetobacter* sp. and a sulfate-reducing bacterial consortium from ethanol fuel environments on fatigue crack propagation in pipeline and storage tank steels. *Corros Sci* 2014; 79: 128–138.
- Stipaničev M, Rosas O, Basseguy R, Turcu F. Electrochemical and fractographic analysis of microbiologically assisted stress corrosion cracking of carbon steel. *Corros Sci* 2014; 80: 60–70.
- Takahashi K, Tsunoi S, Hara T, Ueno T, Mikami A, Takada H, Ando K, Shiratori M. Experimental study of low-cycle fatigue of pipe elbows with local wall thinning and life estimation using finite element analysis. *Int J Pres Ves Pip* 2010; 87: 211–219.
- Thomas CJ, Edyvean RGJ, Brook R, Austen IM. The effects of microbially produced hydrogen sulphide on the corrosion fatigue of offshore structural steels. *Corros Sci* 1987; 27: 1197–1204.
- Tsokur NI, Kobzaruk AV. Corrosion and corrosion-fatigue properties of 10KhSND steel in natural sea water and in a medium saturated with marine bacteria. *Mater Sci* 1984; 20: 122–124.
- Turnbull A. Comparison of hydrogen charging of structural steel by crack tip processes and by bulk reactions in the cathodic protection of corrosion fatigue cracks. *Scripta Metal* 1986; 20: 365–369.
- Vaidya RU, Butt DP, Hersman LE, Zurek AK. Effect of microbiologically influenced corrosion on the tensile stress-strain response of aluminum and alumina-particle reinforced aluminum composite. *Corrosion* 1997; 53: 136–141.
- Venzlaff H, Enning D, Srinivasan J, Mayrhofer KJJ, Hassel AW, Widdel F, Stratmann M. Accelerated cathodic reaction in microbial

- corrosion of iron due to direct electron uptake by sulfate-reducing bacteria. *Corros Sci* 2013; 66: 88–96.
- von Wolzogen Kuhr CAH, van der Vlugt LS. Graphitization of cast iron as an electrochemical process in the anaerobic soils. *Water (The Hague)* 1934; 18: 147–155.
- Vosikovskiy O, Rivard A. The effect of hydrogen sulfide in crude oil on fatigue crack growth in a pipe line steel. *Corrosion* 1982; 38: 19–22.
- Wang D, Xie F, Wu M, Liu G, Zong Y, Li X. Stress corrosion cracking behavior of X80 pipeline steel in acid soil environment with SRB. *Metall and Mat Trans A* 2017a; 48: 2999–3007.
- Wang D, Xie F, Wu M, Sun D, Li X, Ju J. The effect of sulfate-reducing bacteria on hydrogen permeation of X80 steel under cathodic protection potential. *Int J Hydrogen Energy* 2017b; 42: 27206–27213.
- Wilmott MJ, Jack TR, van Boven G, Sutherby RL. Pipeline stress corrosion cracking: crack growth sensitivity studies under simulated field conditions, *Corrosion/96*, NACE. Houston, TX, 1996.
- Wu T, Xu J, Sun C, Yan M, Yu C, Ke W. Microbiological corrosion of pipeline steel under yield stress in soil environment. *Corros Sci* 2014a; 88: 291–305.
- Wu T, Xu J, Yan M, Sun C, Yu C, Ke W. Synergistic effect of sulfate-reducing bacteria and elastic stress on corrosion of X80 steel in soil solution. *Corros Sci* 2014b; 83: 38–47.
- Wu T, Yan M, Zeng D, Xu J, Sun C, Yu C, Ke W. Hydrogen permeation of X80 steel with superficial stress in the presence of sulfate-reducing bacteria. *Corros Sci* 2015a; 91: 86–94.
- Wu T, Yan M, Zeng D, Xu J, Sun C, Yu C, Ke W. Stress corrosion cracking of X80 steel in the presence of sulfate-reducing bacteria. *J Mater Sci Technol* 2015b; 31: 413–422.
- Wu TQ, Yan MC, Zeng DC, Xu J, Yu CK, Sun C, Ke W. Microbiologically induced corrosion of X80 pipeline steel in a near-neutral pH soil solution. *Acta Metall Sin (Engl Lett)* 2015c; 28: 93–102.
- Wu T, Yan M, Xu J, Liu Y, Sun C, Ke W. Mechano-chemical effect of pipeline steel in microbiological corrosion. *Corros Sci* 2016; 108: 160–168.
- Wu T, Sun C, Ke W. Interpreting microbiologically assisted cracking with E° -pH diagrams. *Bioelectrochemistry* 2018a; 120: 57–65.
- Wu T, Sun C, Xu J, Yan M, Yin F, Ke W. A study on bacteria-assisted cracking of X80 pipeline steel in soil environment. *Corros Eng Sci Technol* 2018b; 53: 265–275.
- Xu LY, Cheng YF. An experimental investigation of corrosion of X100 pipeline steel under uniaxial elastic stress in a near-neutral pH solution. *Corros Sci* 2012; 59: 103–109.
- Xu D, Gu T. Carbon source starvation triggered more aggressive corrosion against carbon steel by the *Desulfovibrio vulgaris* biofilm. *Int Biodeterior Biodegrad* 2014; 91: 74–81.
- Xu D, Li Y, Song F, Gu T. Laboratory investigation of microbiologically influenced corrosion of C1018 carbon steel by nitrate reducing bacterium *Bacillus licheniformis*. *Corros Sci* 2013; 77: 385–390.
- Xu D, Li Y, Gu T. Mechanistic modeling of biocorrosion caused by biofilms of sulfate reducing bacteria and acid producing bacteria. *Bioelectrochemistry* 2016; 110: 52–58.
- Xu D, Xia J, Zhou E, Zhang D, Li H, Yang C, Li Q, Lin H, Li X, Yang K. Accelerated corrosion of 2205 duplex stainless steel caused by marine aerobic *Pseudomonas aeruginosa* biofilm. *Bioelectrochemistry* 2017; 113: 1–8.
- Yu L, Duan J, Du X, Huang Y, Hou B. Accelerated anaerobic corrosion of electroactive sulfate-reducing bacteria by electrochemical impedance spectroscopy and chronoamperometry. *Electrochem Commun* 2013; 26: 101–104.
- Yuan S, Liang B, Zhao Y, Pehkonen SO. Surface chemistry and corrosion behaviour of 304 stainless steel in simulated seawater containing inorganic sulphide and sulphate-reducing bacteria. *Corros Sci* 2013; 74: 353–366.
- Zhang P, Xu D, Li Y, Yang K, Gu T. Electron mediators accelerate the microbiologically influenced corrosion of 304 stainless steel by the *Desulfovibrio vulgaris* biofilm. *Bioelectrochemistry* 2015; 101: 14–21.
- Zhao Y, Zhou E, Liu Y, Liao S, Li Z, Xu D, Zhang T, Gu T. Comparison of different electrochemical techniques for continuous monitoring of the microbiologically influenced corrosion of 2205 duplex stainless steel by marine *Pseudomonas aeruginosa* biofilm. *Corros Sci* 2017; 126: 142–151.
- Zhou E, Li H, Yang C, Wang J, Xu D, Zhang D, Gu T. Accelerated corrosion of 2304 duplex stainless steel by marine *Pseudomonas aeruginosa* biofilm. *Int Biodeterior Biodegrad* 2018; 127: 1–9.
- Zucchi F, Grassi V, Monticelli C, Trabanelli G. Hydrogen embrittlement of duplex stainless steel under cathodic protection in acidic artificial sea water in the presence of sulphide ions. *Corros Sci* 2006; 48: 522–530.